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DESIGN STUDY OF A HIGH
POWER ROTARY TRANSFORMER



by

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16. Abstract A design study was made on a rotary transformer for transferring electrical power across a rotating spacecraft interface. The analysis was performed for a 100 KW, 20 KHz unit having a "pancake" geometry. The rotary transformer had a radial (vertical) gap and consisted of 4-25 KW modules. It was assumed that the power conditioning comprised of a Schwarz resonant circuit with a 20 KHz switching frequency. The study covered the rotary transformer, mechanical and structural design, heat rejection system and drive mechanism providing a complete power transfer device. The rotary transformer losses, efficiency, weight and size were compared with an axial (axial symmetric) gap transformer having the same performance requirements and input characteristics which had been designed as part of a previous program. The "pancake" geometry results in a heavier rotary transformer primarily because of inefficient use of the core material. The present study shows that the radial gap rotary transformer is a feasible approach for the transfer of electrical power across a rotating interface and can be implemented using presently available technology.			
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SUMMARY

A study was made of a 100 KW rotary power transformer for transferring electrical power across a rotating spacecraft interface between solar arrays and the spacecraft body. The rotary transformer had a "pancake" geometry, i.e., a large diameter and short length. This was accomplished by utilizing a 4-25 KW transformer modules, with the modules having radial (vertical gaps) and arranged concentrically, one inside-another. The study covered the rotary transformer, mechanical design, structural design, heat rejection system, and drive mechanism. A comparison was made of the axial gap (axial symmetric) rotary transformer and power transfer device designed as part of "Preliminary Design Development of 100 KW Power Transfer Device", Report NASA-CR 165431.

This study showed that a 100 KW radial gap rotary transformer having a "pancake" geometry is feasible. The radial gap transformer is heavier than the axial gap, weighing 75.7 lbs. as compared with 46.4 lbs., principally due to the less efficient use of the core material in the modules. Some weight reduction could be attained by a more detailed design analysis or by application of advanced materials. The weight of the rotary power transfer device with attendant equipment for the radial gap configuration is 225.4 lbs., while that of the comparable axial gap device is 191.8 lbs. The rotary transformer assembly weighs approximately one-half of the weight of the complete power transfer device and the rotary transformer contributes about one-third of the total weight. The size of the radial gap transformer is 17.3 inches diameter and 2.625 inches long; and that of the rotary transformer assembly is 17.3 inches diameter and 6.6 inches long.

The radial gap transformer can be implemented with present state-of-the-art technologies; however, some development might be necessary for the heat pipes. It was recommended that a 25 KW, 20 KHz, rotary transformer and power conditioning electronics be built and tested.

1.0 INTRODUCTION

The power requirements for future spacecraft appear to be in the magnitude of 100 KW to 1 MW. Spacecraft which have sun-oriented arrays require a means of transferring the power across the rotating interface between the solar arrays and the spacecraft body. In present day spacecraft where the power requirements are several kilowatts, the power transfer is accomplished by brushes riding on slip rings. Techniques other than brushes and slip rings have been addressed to meet the needs for higher power as well as the necessity for higher voltages and long operational life. Typically advanced applications for rotary joints will require a 10 year life time and work through 50,000 cycles.

A study of non-contacting, alternating current power transfer devices was performed in the "Preliminary Design Development of 100 KW Rotary Power Transfer Device", Report NASA CR-165431 under Contract NAS 3-22266. This study showed that a rotary transformer was a feasible concept for the transfer of electrical power. As part of the study, a 100 KW rotary power transfer device was designed. The power transfer device consisted of a rotary transformer, power conditioning electronics, drive mechanism and heat rejection system. The rotary transformer had an axial gap (axial symmetric) and utilized 4-25 KW modules placed along the shaft axis. Although this approach is quite feasible, its inherent geometry is one of relatively long length and small diameter.

This study was undertaken to investigate a radial gap (vertical gap) rotary transformer and to compare its characteristics with that of the axial gap configuration. The radial gap rotary transformer was to have a pancake configuration: large diameter and short length, a geometry could be more favorable from the aspect of spacecraft considerations. The pancake configuration would be achieved by using radial gap

transformer modules stacked radially one-inside-another. This approach is a little more complex than that of the axial gap transformer. The major concerns with the radial gap geometry are the heat rejection system, the inefficient use of the core material resulting from the large diameter, and the necessity for having four modules, each having different cores and windings.

An additional part of this study was a comparison of the radial and axial rotary transformers. This comparison covered weight, size, losses, efficiency and reliability focusing on the characteristics of the 25 KW modules as well as the 100 KW assembly.

2.0 REQUIREMENTS

The requirements for the Rotary Power Transfer Device were derived from LeRC, some of the recommendations presented by the General Dynamics "Study of Power Management for Orbital Multi-100 KWe Applications", NASA CR-159384; and consistency with "Preliminary Design Development of 100 KW Rotary Power Transfer Device", NASA CR-165431. The requirements which were used as guidelines are as follows:

Input from Solar Array

Power	100 KW
Voltage	440 Volts

Output from Rotary Power Transfer Device

Voltage	1000 Volts
Frequency	20 KHz

Power Conditioning Electronics

Resonant Circuit (Schwarz)

Rotary Transformer

Power	100 KW
Input Voltage	400 Volts
Input Current	70 Amps
Output Voltage	1000 Volts
Frequency	20 KHz
Inductance	75 μ H
Configuration	Radial Gap 4-25 KW modules Two parallel secondary windings per module

<u>Rotational Period</u>	90 minutes to 24 hours
<u>Efficiency</u>	Greater than 95%
<u>Environment</u>	Shuttle Launch
<u>Temperature</u>	
- Non-operating	-20° to 80°C
- Operating	80° Heat Sink, Rotary Transformer 60° Heat Sink, Power Conditioning Electronics
<u>Life</u>	5 Years

3.0 ROTARY TRANSFORMER DESIGN

The rotary transformer transfers electrical power across the spacecraft interface by means of electromagnetic coupling between the transformer primary and secondary. The transformer primary consists of a core and winding, and is mechanically attached and connected electrically to the solar array through power conditioning electronics. The transformer secondary, also consisting of a core and winding, is mechanically attached to the spacecraft and its electrical power is delivered to the spacecraft load. The electrical solar array power is converted from dc to 20 KHZ ac by the power conditioning electronics which is a Schwarz resonant circuit. The heat which is generated by I^2R and core losses in the transformer primary and secondary is transported by heat pipes to thermal ejection surfaces. Rotational capability ranging from one revolution per day to one revolution every 90 minutes is provided by a stepper motor, speed reducer, and associated drive electronics.

The radial gap (vertical gap) transformer module configuration is more complex than the previously studied axial gap (axial symmetric) module geometry. In the axial gap configuration, all modules were identical: cores, windings, resistance, inductance and losses were the same. In the radial gap configuration, the modules being "stacked" radially on each other are all different. This means that each transformer module has a different core, different winding, and different losses. There is nothing inherently wrong with this, but it does add to the complexity of the approach.

A more serious problem with the radial gap configuration is in the heat rejection system. In both radial and axial gap transformers, heat pipes are used to transport the heat from the transformer modules to the heat sink. In the axial gap, the heat pipes transport the heat only in one direction, axially, parallel to the shaft axis.

In the radial gap configuration, the problem is more difficult because the transformer cores have different diameters. Axial heat pipes could be used directly connecting each individual module to the heat sink; however, this would lead to a complex structure and excessive weight. An alternative heat rejection method entailing a combination of radial and axial pipes. The radial heat pipes would be attached to the transformer cores and would transfer heat radially to the axial heat pipes, and the axial heat pipes would then transfer heat axially to the heat rejection surfaces. The radial and axial heat pipes could be separate, but this would lead to a large thermal gradient between the two sets of pipes at their interface. This thermal gradient could be reduced by having a large contact surface area but this would entail heat pipe overlap and a substantial weight increase. The proposed solution is to make the radial and axial heat pipes into a single integral unit. This is a more complex heat pipe but would result in a better overall design.

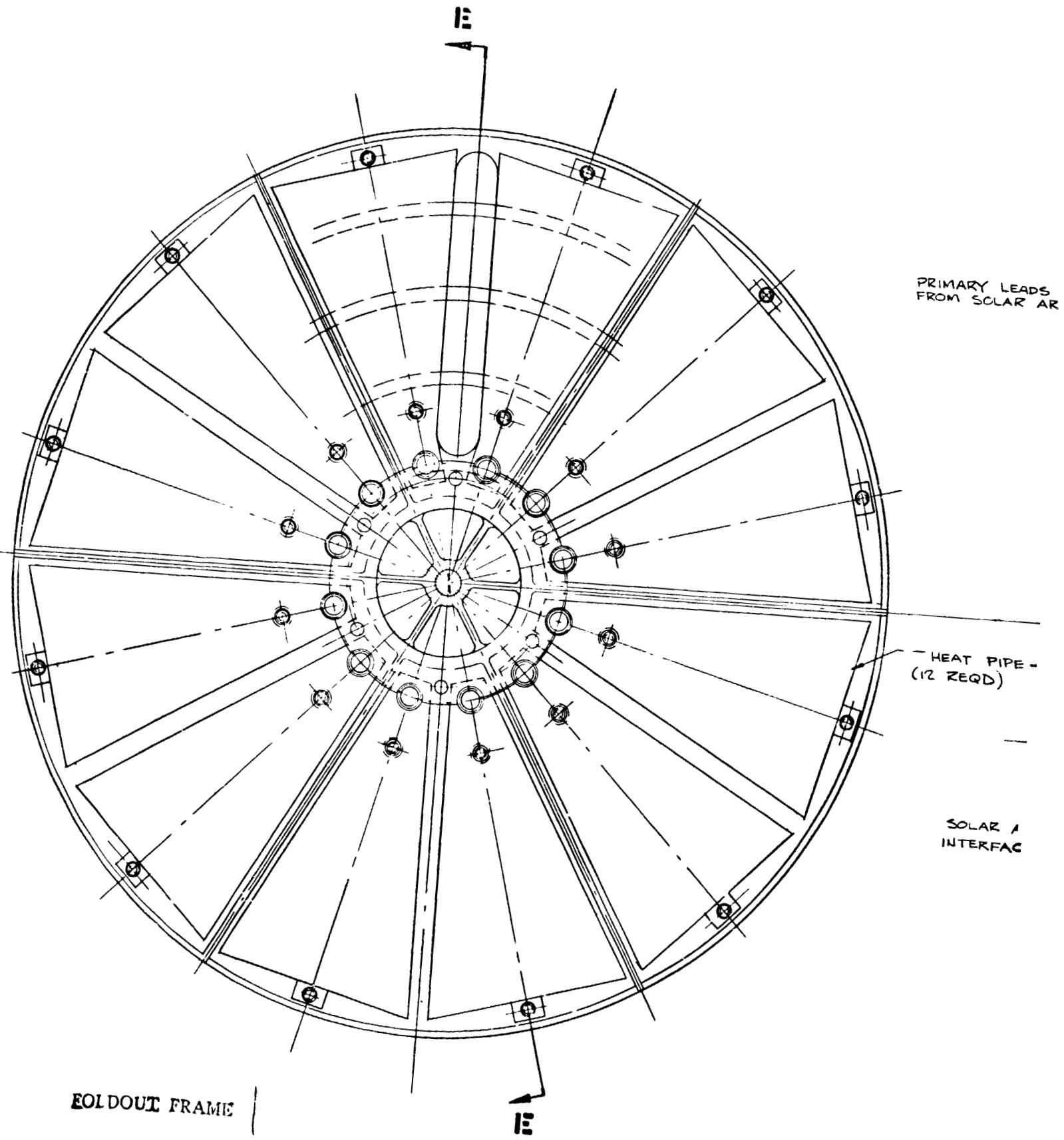
The selection of materials for the rotary transformer is quite important as they just be compatible with each other and in the function that they are expected to perform. Table 3.1 shows the materials used on the rotary transformer, the reasons for their selection and their limitations. It provides the rationale for the materials chosen for the various design areas.

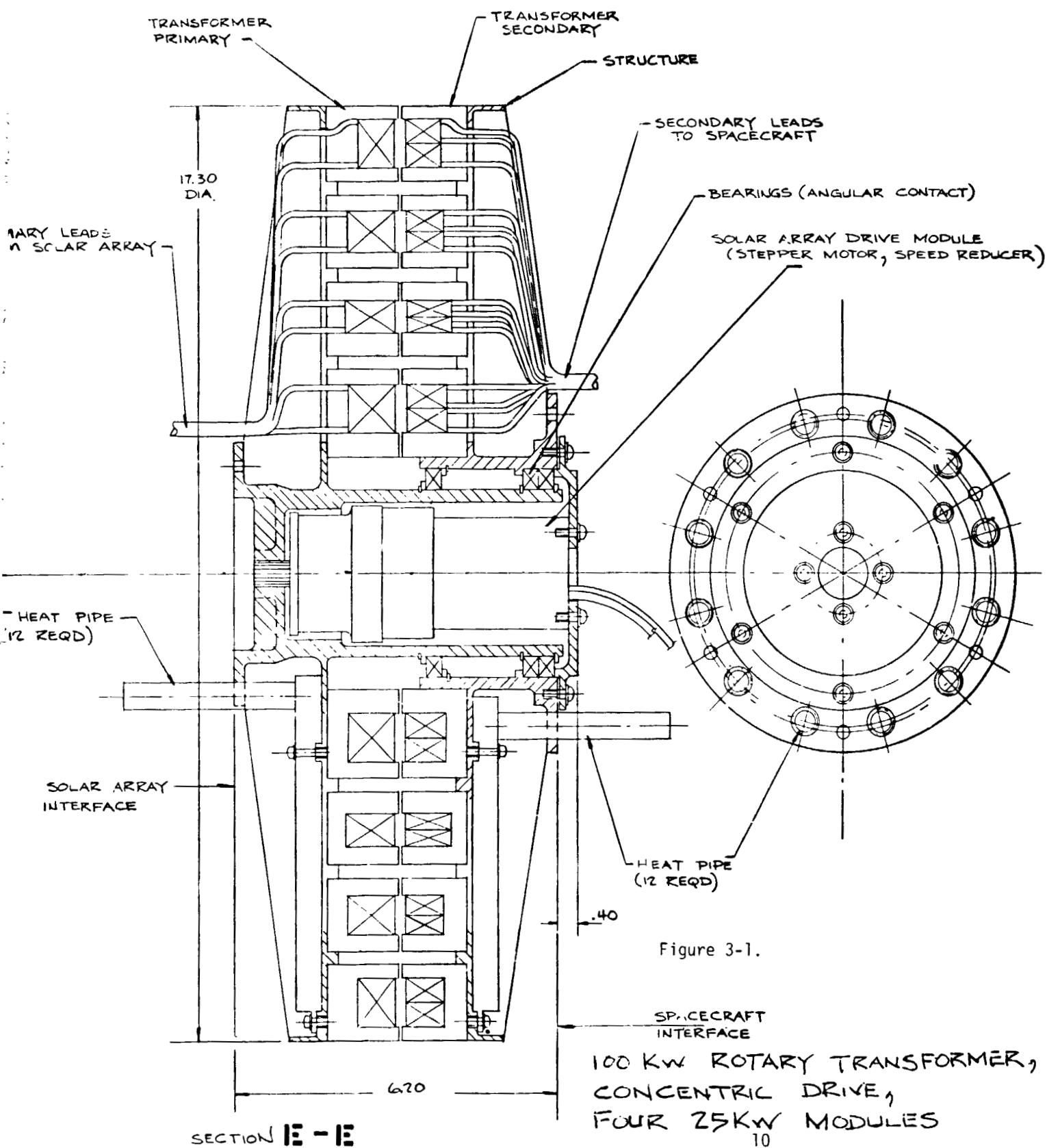
The design configuration for the rotary transformer is shown in Figure 3.1, 100 KW Rotary Transformer. This figure shows a complete rotary power transfer device: radial gap rotary transformer modules, structures, heat pipes and drive mechanism. The overall configuration is a "pancake": a large diameter and small length.

Table 3.1. Material Selection Criteria

Design Area	Material	Reason for Selection	Limitations
Magnetic	MN 60 Ferrite	a) Isotropic b) Low core loss c) High permeability	a) Flux density/temperature b) Coefficient of expansion c) Low thermal conductivity d) Low strength
Electrical	Litz Wire Nyleze	a) Low eddy current loss b) Solderable	a) Connections b) Life/temperature
Mechanical	Inconel Structures	a) Coefficient of expansion b) Non-magnetic	a) Fabrication b) Weight c) Availability
Thermal	Inconel heat pipes, radial/ axial Radiator Thermally conducting epoxy	a) Coefficient of expansion b) Thermal gradients Thermal dissipation Thermal conductivity	a) Weight b) Availability a) Size, weight a) Shear strength b) Bond-line thickness

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2 FOLDOUT FRAME

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3.1 CORE DESIGN

The primary and secondary transformer cores are fabricated from MN 60, a maganese zinc ferrite material made by Ceramic Magnetics, Inc. This material was selected because of its being magnetic isotropic and having low core losses. The use of any ferrite material imposes magnetic, thermal and mechanical constraints on the rotary transformer design. Some of the properties of MN60 and their effects are as follows:

<u>Property</u>	<u>Effects</u>
Maximum operating flux density is a function of temperature.	Core size affected operating temperature. Thermal run-away could occur
Temperature (°C)	B max (Gauss)
75	3500
100	3000
125	2400
150	1400
185	0 (Curie point)
Coefficient of thermal expansion.	Structure, shaft heat pipes cannot be fabricated from aluminum or titanium, Inconel used.
$\alpha = 11.5 \times 10^{-6} /{ }^{\circ}\text{C}$	
Low thermal conductivity.	Large circumferential thermal gradients in cores if few heat pipes used.
$K = 3.6 \text{ BTU/hr/ft}^2 /{ }^{\circ}\text{F/ft}$	
Mechanically weak	Minimum allowable thickness, 0.2". Cores thicker than required for magnetic reasons.

The primary and secondary core geometries are shown in Figure 3.2. They are fabricated from rings having a circumferential groove cut into their sides to accommodate the windings. Since the maximum diameter of ring which can be easily fabricated is about eight inches, transformer modules having ring diameters in excess of eight inches would be made by fabricating the ring in segments. These segments would then

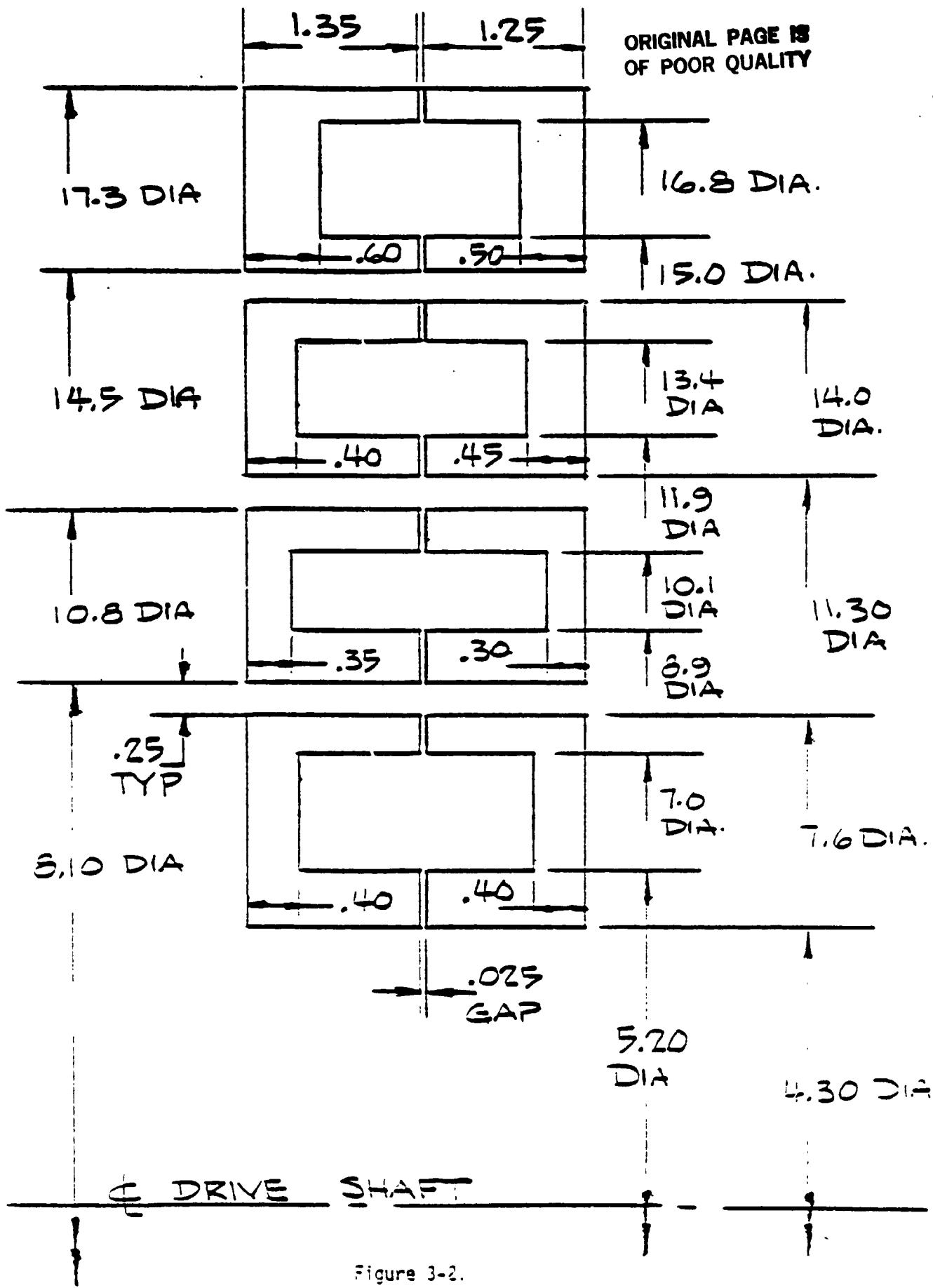


Figure 3-2.

PRIMARY & SECONDARY CORES

be bonded together to form the core assembly. The length of gap between the segments would not be critical because they are not in the path of the magnetic flux, however, it should be kept small in order to minimize the reluctance torques which arise when the gaps in the primary and secondary cores are in alignment. The power leads to the windings would be brought out through slots cut in the cores.

The widths of the primary and secondary cores were kept identical, 1.35 inches and 1.25 inches, respectively, in order to simplify the mechanical and structural design of the rotary transformer. Keeping the core widths identical is not optimum from the aspect of magnetic circuit design since the larger diameter modules do not require the same dimensions as the smaller diameter modules to maintain the required flux density. If the core widths were established strictly by magnetic design criteria, the structure would be larger and heavier than necessary so that there would be no advantage attained.

In Figures 3.3 and 3.4, 25 KW Rotary Transformer Module, Primary and Secondary, respectively, show the winding and core assemblies, and the materials used. The 25 KW Module Configuration is shown in Figure 3.5. The Assembly Detail of the cores, winding, heat pipes and structure is shown in Figure 3.6.

Table 2, Transformer Module Magnetic Parameters, shows the magnetic characteristics of the transformer modules. Although the ferrite core material can operate at flux densities up to approximately 2,000 gauss at 125°C, the actual flux densities are much less, primarily because of mechanical constraints. For example, the flux densities in Module 4 range between 664 gauss and 1,621 gauss, considerably less than 2,000 gauss.

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EPOXY,
ECCOBOND 45

COVER COIL WITH
FIBERMATTE TAPE
3M # 2540 AND TAPE
3M # 79

1.35

BOBBIN
MELAMINE GLASS

.015
TYP

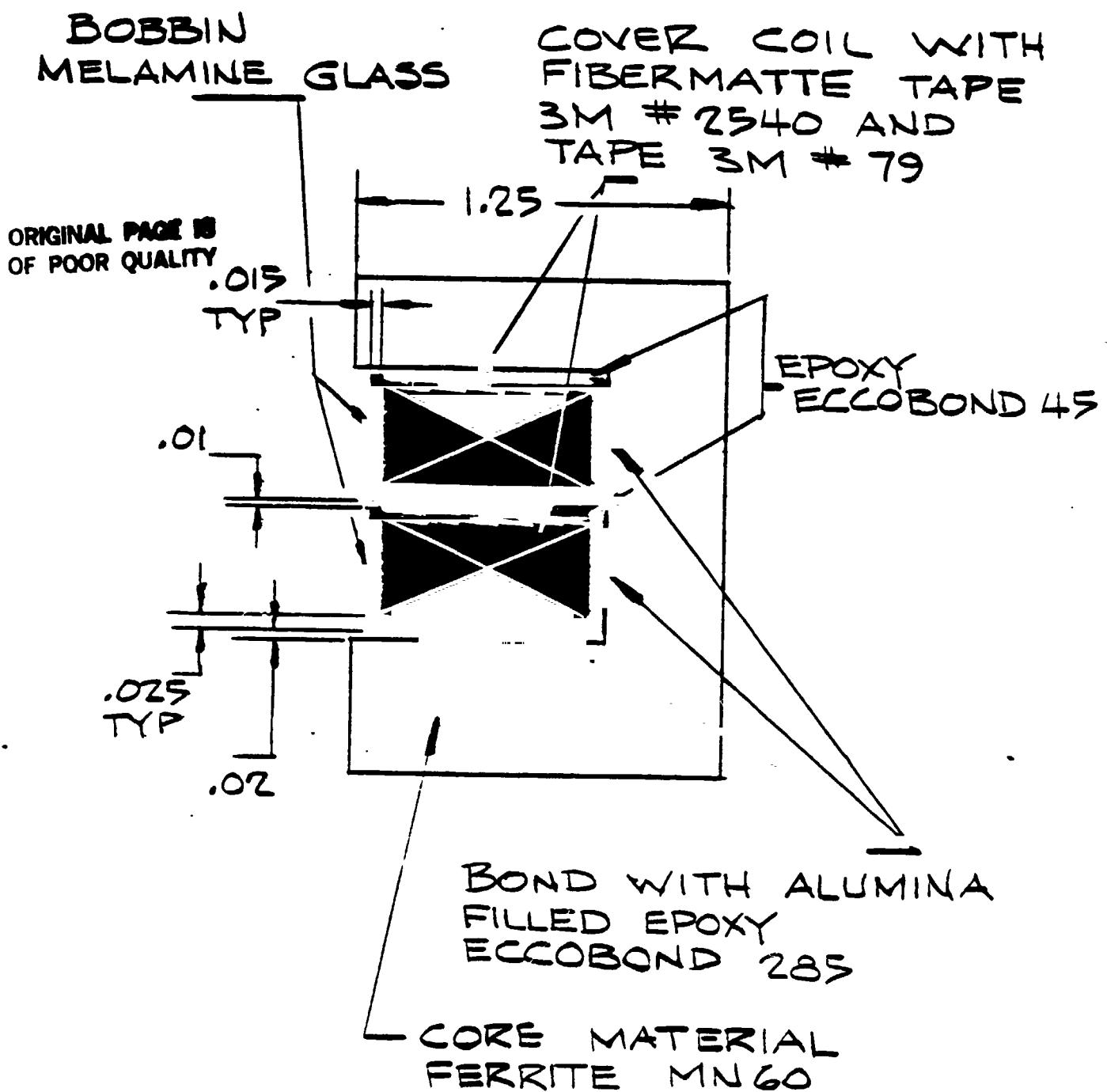
.025
.02

BOND WITH ALUMINA
FILLED EPOXY,
ECCOBOND 285

CORE MATERIAL:-
FERRITE MN 60

ASSEMBLY, PRIMARY,
25KW ROTARY TRANSFORMER MODULE

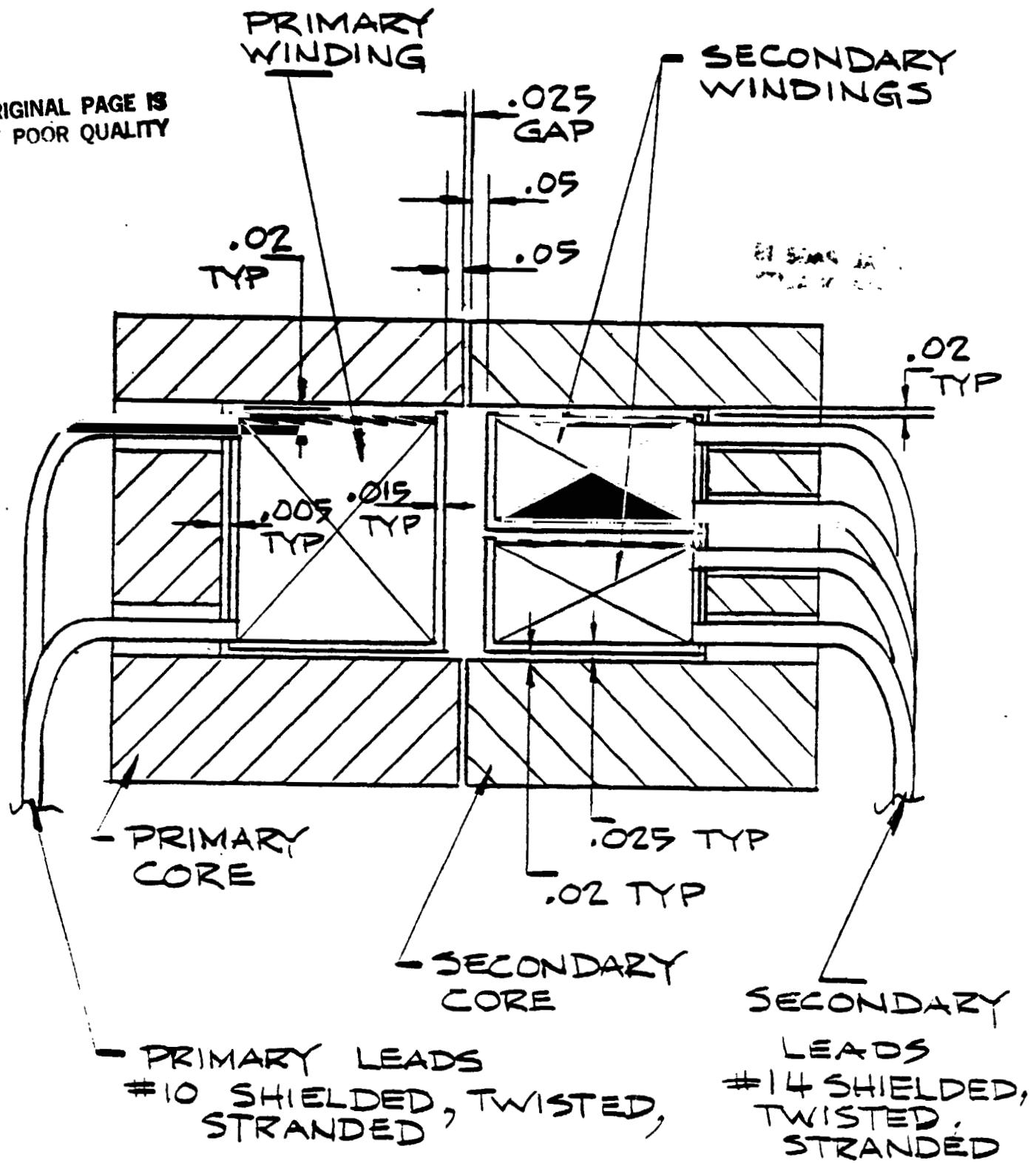
Figure 3-3.



ASSEMBLY, SECONDARY,
25 KW ROTARY TRANSFORMER MODULE

Figure 3-4.

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25KW MODULE DETAIL

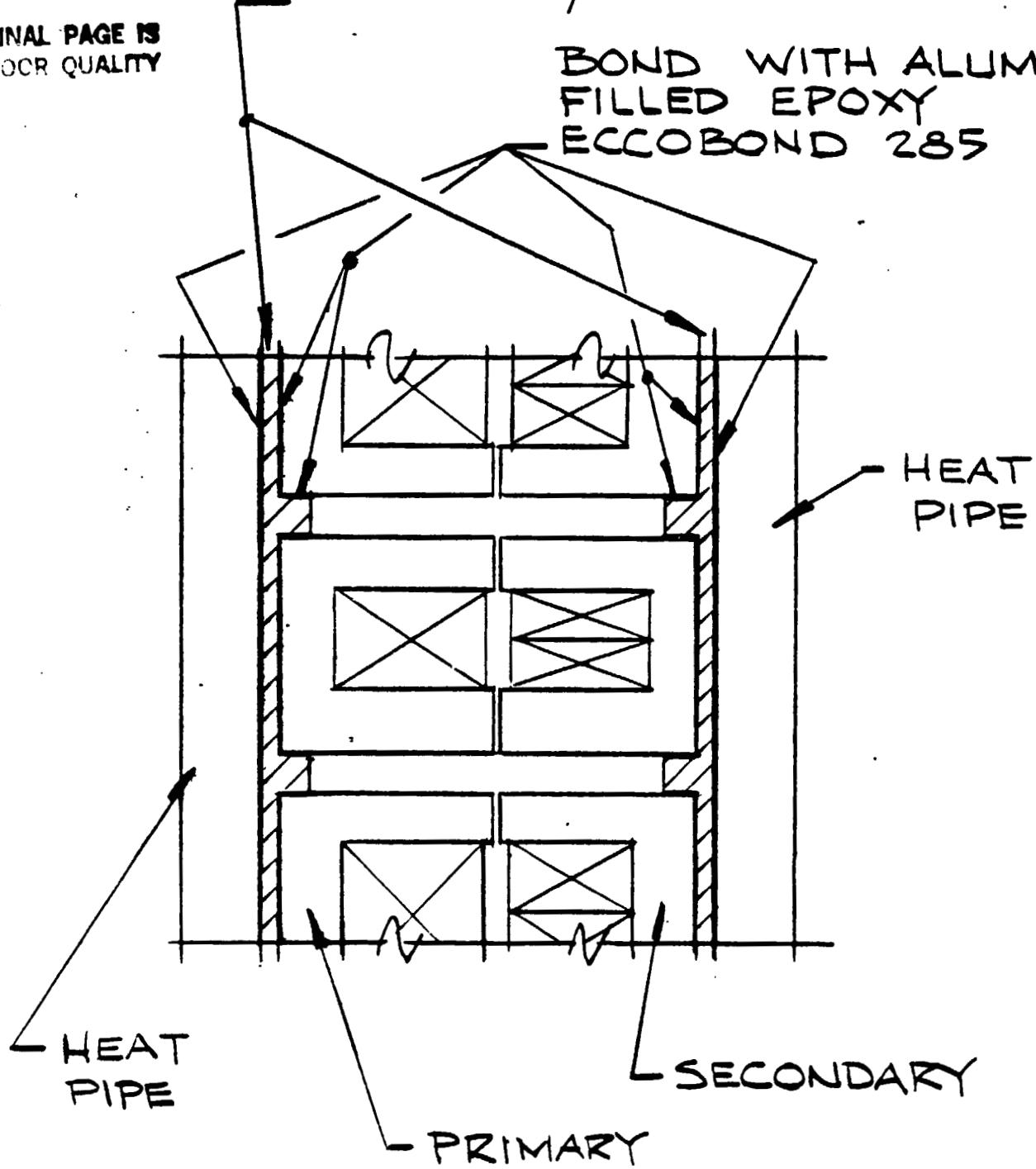
ROTARY TRANSFORMER.

Figure 3-5.

STRUCTURE, INCONEL 722

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BOND WITH ALUMINA
FILLED EPOXY
ECCOBOND 285



ASSEMBLY DETAIL TRANSFORMER MODULES

Figure 3-6.

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Table 3.2. Transformer Module Magnetic Parameters

Flux Density (gauss)	1	2	Module	3	4
Primary Pole, Lower	1865	1758	1718	1621	
Upper	1820	1635	1455	1402	
Primary Core, Root	1915	1918	1255	664	
Secondry Pole, Lower	1865	1758	1718	1621	
Upper	1820	1635	1455	1402	
Secondary Yoke, Root	1915	2238	1155	797	
Core Loss (Watts)					
Primary	45	67	58	80	
Secondary	43	60	57	70	
Weights (lbs.)					
Primary Core	4.4	6.4	7.6	10.5	
Secondary Core	4.2	5.7	7.5	9.3	

The radial gap transformer geometry present mechanical and structural requirements which are more severe than in the axial gap configuration. These are caused by the large module diameter and magnetic forces. The diameter of the outermost radial gap transformer module is 17.3 inches. Although these core diameters can be obtained by bonding smaller segments together to form a ring, their manufacture and assembly does present a possible concern. In the radial gap geometry, there are magnetic forces

present in the axial direction tending to pull the modules together. The magnetic forces are estimated to be approximately 130 lbs. It is desirable to keep the length of gap between the primary and secondary cores as small as possible to minimize the magnetizing current. A gap length of .025" was selected as the minimum attainable based on mechanical and structural considerations. It is, therefore, necessary to have a structure rigid enough to maintain the gap length and its parallelism.

3.2 WINDINGS

The input power to the rotary transformer originates in the solar array as DC and is converted by a Schwarz resonant circuit power conditioning to 20 KHz AC. The output of the secondary winding of the transformer feeds into the spacecraft at a stepped-up voltage of 1,000 volts. In order to permit some degree of flexibility and redundancy, the secondary was designed having two independent windings, each capable of supplying 12.5 KW per module. The use of the Schwarz resonant circuit imposes the inductance requirement of 75 μ H for each transformer module. If the inductance is different from this, there will be a change in the switching frequency of the resonant circuit.

A trade-off was made to determine the best winding design. Some of the winding parameters which were addressed included number of turns, wire size, turn size, losses, and inductance. Generally, as the number of primary turns is increased, the inductance, copper loss, winding area and number of secondary turns increase while the core cross section area and flux density decrease. For mechanical reasons, it is desirable to have primary and secondary leads come out the same side of the core, the number of layers must be even. In addition, the number of primary and secondary turns must be an integer.

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The voltage ratio between the primary and secondary windings affect the number of turns which can be used on the primary winding. The turns ratio between the primary and secondary is defined as the turns ratio:

$$\text{Turns Ratio} = \text{Voltage Ratio} = \frac{\text{Secondary Voltage}}{\text{Primary Voltage}}$$

$$\text{Turns Ratio} = \frac{1000}{400} = 2.5$$

The following shows the number of turns on the primary and secondary windings which are satisfactory and which are not satisfactory.

Primary Turns (N _p)	Secondary Turns (N _s) (N _s = 2.5 N _p)	Comments
16	40	Satisfactory
15	37.5	Unsatisfactory N _p is odd N _s is a fraction
14	35	Unsatisfactory N _s is odd
13	32.5	Unsatisfactory N _p is odd N _s is a fraction
12	30	Satisfactory
11	27.5	Unsatisfactory N _p is odd N _s is a fraction
10	25	Unsatisfactory N _s is odd

Because of the high frequency transformer operation, and the necessity of keeping the eddy current losses to a minimum, the primary and secondary windings were designed with insulated, stranded, transposed conductor in the form of Litz wire. Litz wire is available commercially over a wide range of sizes from specialty wire manufacturers. Two major disadvantages of Litz wire are the reduction in winding space factor resulting from the stranding and transportation, and the design connector to the power leads. The Litz wire conductor insulation will be heavy polyurethane with nylon overcoat with the trade name Nyleze. This is a solderable coated wire with good winding characteristics and is compatible with most impregnants.

The requirements of the Schwarz resonant circuit define an input inductance of each module as being $75\mu\text{H}$. In the axial gap rotary transformer, the inductance was achieved by using a magnetic shunt whose geometry could be changed. Magnetic shunts were not used in the radial gap design because of the weight and the different sizes necessary for each module. Instead, the required inductance was obtained by the selection of the number of turns and the winding slot geometries of the primary and secondary cores.

The winding design for each of the transformer modules is shown in Table 3.3. The winding design for each module is different as the direct result of differences in module diameter and reflects the requirements of inductance, losses and temperature rise.

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Table 3.3. Transformer Module Winding Design

Module	1	2	3	4
Primary Winding	12	8	8	8
Turns/Winding	3	4	2	2
Turns/Layers	4	2	4	4
Wire Size, Stranding	#38, 2025	#38, 1980	#38, 2100	#38, 2025
Turn Size	.2" x .2"	.161" x .244"	.157" x .266"	.2" x .2"
Resistance (ohms) @ 135°C	.0148 dc .0192 ac	.0157, dc .0203, ac	.0197, dc .0238, ac	.0257, ac .0291, ac
$I^2 R_{ac}$ (Watts)	95	99	134	143
Inductance	37.9	38.4	30.0	35.7
Copper Weight (lbs.)	1.2	1.2	1.7	2.1
Secondary Winding				
Turns/Winding	30	20	20	20
Turns/Layer	5	5	5	5
Layers/Winding	6	4	4	4
Windings	2	2	2	2
Wire Size, Stranding	#38, 300	#38, 330	#38, 360	#38, 360
Turn Size	.057" x .113"	.053" x .134"	.070" x .109"	.083" x .092"
Resistance (ohms) @ 135°C	.125, dc .145, ac	.118, dc .142, ac	.138, dc .161, ac	.181, dc .200, ac
$I^2 R_{ac}$ (Watts)	91	89	101	125
Inductance (μ H)	34.3	38.4	36.5	38.9
Copper Weight (lbs.)	1.5	1.7	2.6	3.1

3.3 LEADS

The power leads for the primary and secondary will consist of insulated stranded conductors. The leads will be shielded and used in the form of twisted pairs to minimize electromagnetic interference. The primary leads will be #10 AWG while the secondary will be #14 AWG, the difference being due to the lower current carrying requirements of the secondary.

3.4 STRUCTURE

The basic structural elements of the rotary transformer assembly are ribbed flanged disks having integral annular positioning rings. Two of these disks are used, one for the primary transformer modules and the second for the secondary modules. The transformer module cores are positioned radially on the disk by the annular rings and are bonded to both the rings and disk. The heat pipes are also attached to the flanged disks by bonding and mechanical fasteners. Bonding is essential to providing a good thermal path between the transformer modules and the heat pipes. The primary side of the structure is connected to the solar array through a drive shaft which is an integral part of the disk. The secondary side is attached to the spacecraft by a structural interface flange. The solar array is driven through a preloaded duplex pair of bearings and a single row ball bearing. The primary and secondary transformer leads are brought out through a slot in the structure. The design of the structure must accommodate the axial magnetic forces present and the small clearance between the primary and secondary portions of the rotary transformer.

It would be desirable to fabricate the structure from aluminum for the aspect of weight, ease of fabrication and material availability. However, because of differential expansion between the core and heat pipe materials and the necessity to

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transfer heat across epoxy bonds, aluminum is not a satisfactory material. The following table shows a comparison of the thermal expansion and thermal characteristics of transformer core and structural materials.

	Thermal Expansion (Per °C)	Thermal Conductivity BTU hr/ft ² /°F/in
<u>MN 60 Ferrite</u>	11.5×10^{-6}	43.5
<u>Inconel</u> 702	12.1×10^{-6}	81.0
722	12.1×10^{-6}	102.0
X750	12.6×10^{-6}	83.0
<u>Aluminum 6061</u>	23.4×10^{-6}	1070
<u>Stainless Steel</u> 302	17.3×10^{-6}	113.0
305	16.5×10^{-6}	113.0
309	14.9×10^{-6}	108.0
310	14.4×10^{-6}	98.0
<u>Titanium 6Al-4V</u>	9.0×10^{-6}	50.0

The best approach consists of Inconel structure, Inconel heat pipes in conjunction with the MN 60 ferrite core. The major disadvantages of Inconel is its density, difficulties of fabrication and poor thermal conductivity.

The adhesives will be used in the rotary transformer as follows:

<u>Usage</u>	<u>Adhesive</u>	<u>Function</u>
Core to Structure	Eccobond 285 (Filled)	Mechanical & Thermal
Winding	Eccobond 45 (Unfilled)	Mechanical & Electrical
Bobbin to Core	Eccobond 285 (Filled)	Mechanical & Thermal
Heat Pipes to Structure	Eccobond 285 (Filled)	Mechanical & Thermal

Although filled epoxies necessitate a thicker bond-line than unfilled ones, the thermal resistance to heat flow of the heat flow path through the filled epoxy is less than that of unfilled epoxies. Therefore, filled epoxies will be used in critical heat flow paths.

3.5 ADHESIVES

Epoxy adhesives function in the rotary transformer to bond parts together and to function as a heat conducting joint. A degradation in either their mechanical characteristics or their thermal properties could adversely affect the performance of the transformer. Two types of epoxy adhesives are used in the rotary transformer, unfilled and alumina filled. The alumina filled epoxy is used where required to provide a good thermal path while the unfilled epoxy is used when good thermal conductivity is not required. Unfilled epoxies have higher bond strength, utilize a thinner bond line and have poorer thermal conductivity than filled epoxies. Because of the inherent size of the filler particles filled epoxies require a bond line thickness of about .010".

The following is a summary of the characteristics of the adhesives being considered in the rotary transformer:

	<u>Eccobond 285</u> <u>Alumina Filled Epoxy</u>	<u>Eccobond 45</u> <u>Unfilled Epoxy</u>
Shear Bond Strength (psi)	2100	3100
Flexibility	Rigid	Adjustable
Thermal Conductivity (BTU/hr/ft ² /°F/in)	10.4	2.5
Thermal Expansion Coefficient (10 ⁶ /°C)	15	30
Dielectric Strength (volts/mil)	420	400
Service Temperature (°C max)	177	121

3.6 THERMAL DESIGN

The thermal design is of great importance since it determines the overall size, weight and losses of the rotary transformer. Heat is generated in the rotary transformer from I^2R losses in the windings and from core loss in the ferrite core. The magnitude of these losses can be varied: increasing the cross section of the copper in the windings will decrease the I^2R loss, while decreasing the flux density in the core will decrease the core losses. The penalty for doing this is increased size and weight of the rotary transformer. There are temperature-limited parts in the rotary transformer: windings and cores. The winding temperature is life-limited: the higher the winding temperature, the shorter its life. If the winding temperature is kept at 138°C, it will have a five year life; while at 145°C it will be reduced to 2.3 years. Core temperatures are more serious since an excessive temperature in the core can lead to thermal run-away in the transformer. Core temperatures in excess of 125°C result in lower core magnetic permeability. Reduced core permeability will increase the transfer magnetizing current which, in turn, will increase the winding I^2R losses further increasing the core temperature. The final result will be thermal run-away.

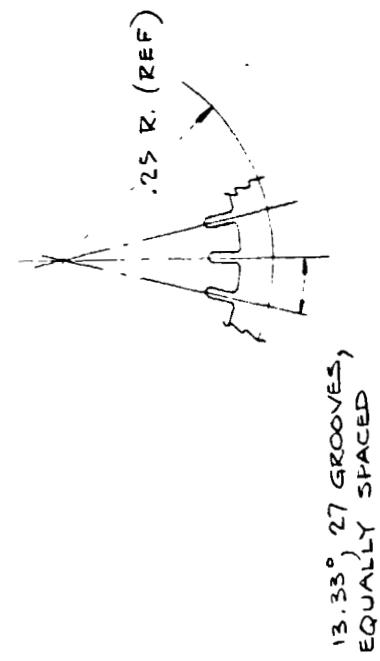
The rotary transformer thermal system is based on heat generated in the being transferred by conduction through the windings and cores to heat pipes placed on the back of the cores, and which transfer the heat to thermal radiators. It is assumed that there is no thermal path between the primary and secondary portions of the transformer.

The losses in the primary rotary transformer and secondary are 721 watts and 636 watts, respectively. Four heat pipes each having a diameter of 1/2 inch have sufficient capacity to remove these losses. However, if four heat pipes of this size were placed on the back of transformer cores there would be large circumferential thermal gradients. These large thermal gradients are the result of the poor thermal conductivities and long thermal paths of small cross sectional area in the ferrite core material and Inconel structure. Large circumferential thermal gradient are undesirable because they will result in hot spots in the winding and core resulting in localized temperatures in excess of those desired. In addition, the failure of one of the heat pipes would be serious.

These concerns with the thermal design are eliminated by using 12 wedge-shaped heat pipes covering most of the core area thus eliminating both the problems of thermal gradients and producing a higher degree of redundancy. These heat pipes provide the radial transfer of heat from the cores to the shaft. Axially, heat transfer is accomplished by circular heat pipes which are integral with the radial wedge-shaped ones. The radial and axial heat pipes will be grooved with a wire mesh or sintered wick acting as the transition between them. This approach is shown in Figure 3-7, Modular Heat Pipe Concept.

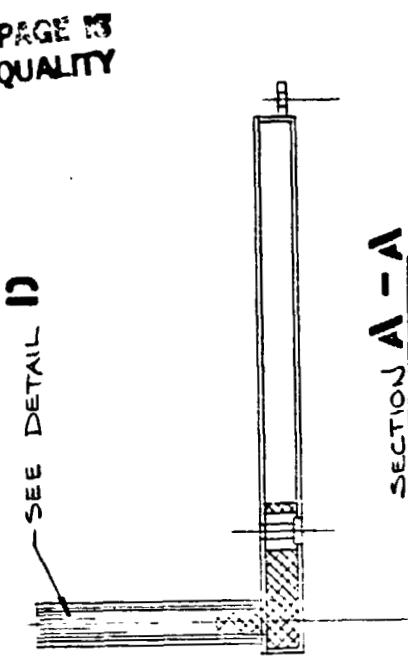
The heat pipe design is complex for several reasons: heat must be transferred in two directions, radial and axial; the radial heat pipe requires converging grooves; a transition is between the radial and axial heat pipes is necessary; and the heat pipe material should be Inconel. Some development effort would probably be required for the heat pipe but the suggested approach appears feasible.

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DETAIL D

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SECTION A-A

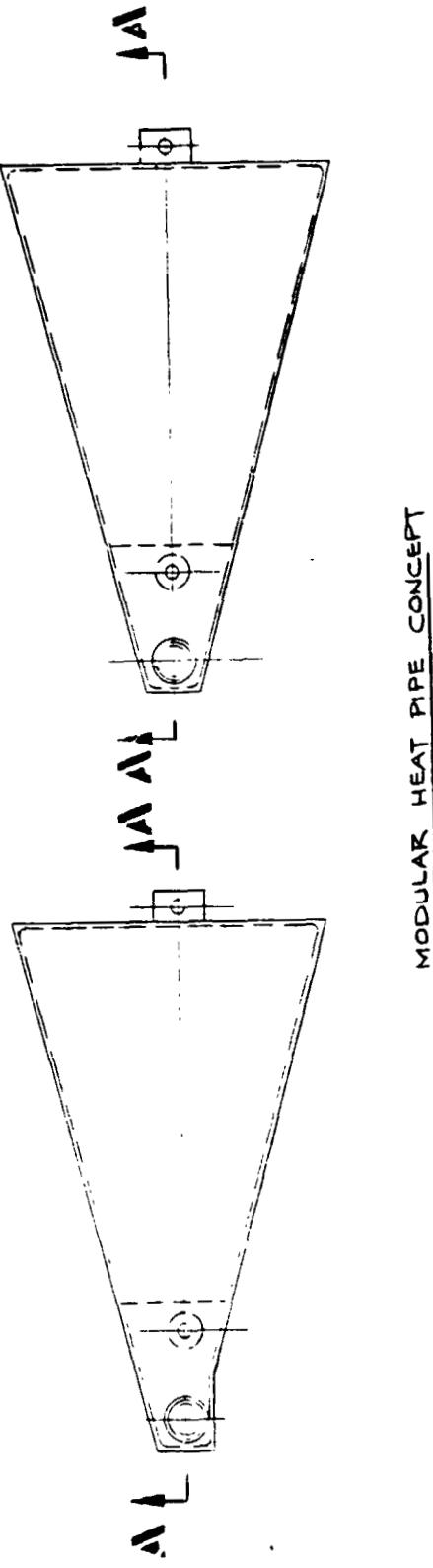


Figure 3-7.

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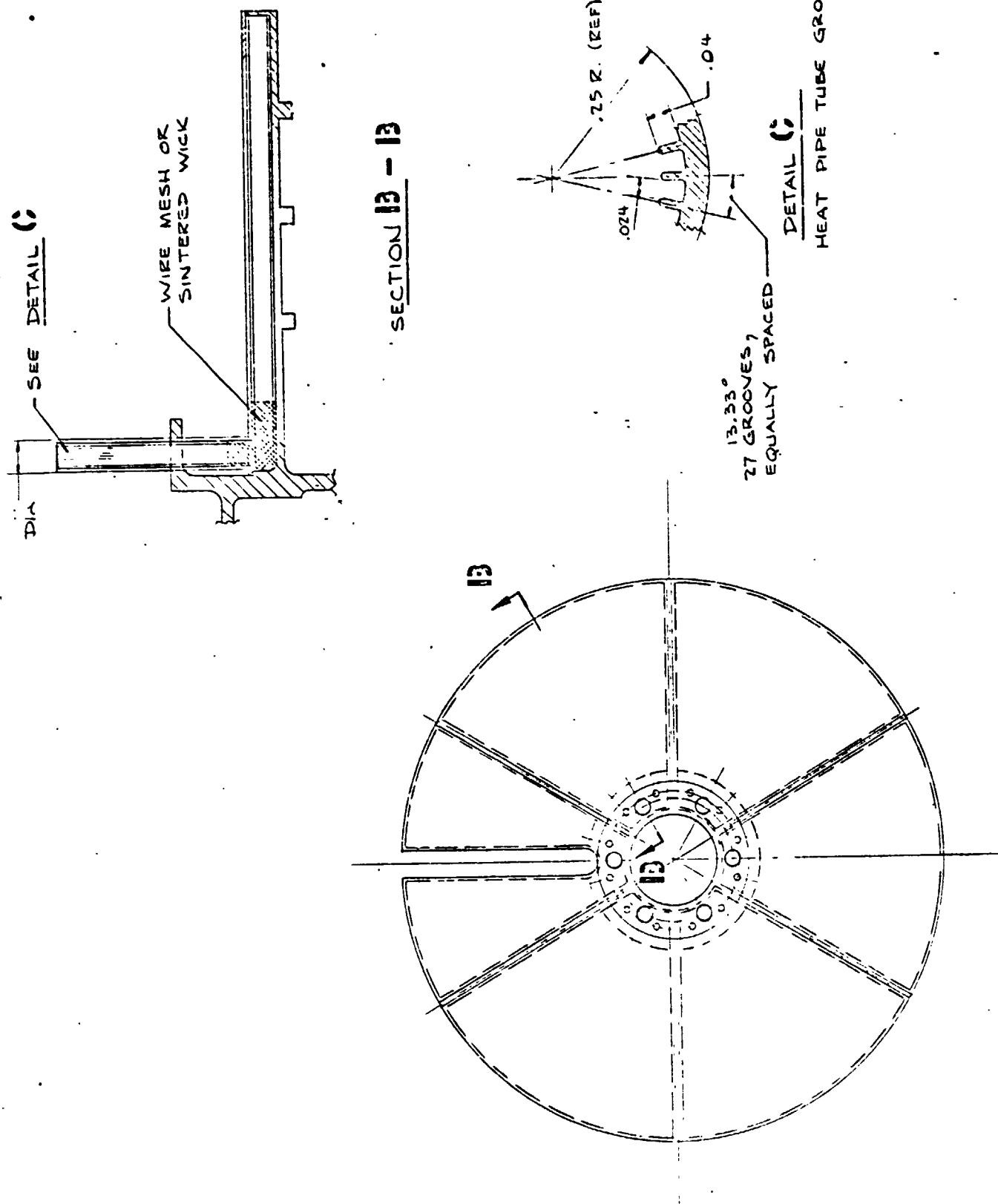


Figure 3-8.

INTEGRAL, STRUCTURAL/HEAT PIPE
CONCEPT

An alternative configuration was considered in which the heat pipe and the structure were one integral unit. This would provide substantial weight advantages since heat pipe would be performing a dual function. Although this approach was deemed to have merit, it was not used because the design would be more complex and would not provide sufficient reliability in the event of a heat pipe failure. The integral, structural/heat pipe concept is shown in Figure 3.8.

The temperature of the rotary transformer primary and secondary cores and windings were calculated for each module. The temperatures for the inner (closer to the shaft) modules tended to be higher than the outer modules even though they had lower losses. This is primarily the result of the better thermal paths of the outer modules. The largest sources of temperature gradient in the rotary transformer were the rewinding bobbin and the ferrite core. In order to keep the bobbin temperature gradient low, the bobbin wall was made as thin as possible, .015" thick, of glass melamine. The thickness of the ferrite core was determined by magnetic and mechanical considerations. Alumina filled epoxy was used to bond the cores and heat pipes to the structure. This epoxy, Eccobond 285, was selected based on its high thermal conductivity and good mechanical properties.

Table 3-4, Transformer Module Temperature Characteristics shows the loss and thermal characteristics of the transformer modules. It will be noted that the temperature rise of the primary windings of Module 3 and Module 4 is approximately 12°C less than that of Modules 1 and 2. This was done to reflect the somewhat poorer heat pipe geometry at the larger diameters which might result from the diverging groove geometry.

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Table 3-4. Transformer Module Temperature Characteristics

Module	Primary Losses (Watts)	Secondary Losses (Watts)	Temperatures (80°C Heat Sink)			
			Primary Core	Winding	Secondary Core	Winding
1	140	134	105°C	124°C	104°C	123°C
2	166	149	103°C	124°C	99°C	120°C
3	192	158	92°C	115°C	97°C	111°C
4	223	195	105°C	115°C	101°C	111°C

3.7 DRIVE MECHANISM

A solar array drive mechanism developed by General Electric is applicable for use as the drive on the rotary transformer. This solar array drive is space qualified and is being used successfully on a number of spacecraft including Landsat D, DSCS, and BSE. The major parts of the solar array drive are the stepper motor and harmonic drive speed reducer. The drive has a resultant output torque of three ft.lbs. and has the capability of providing rotational speeds between one revolution per day to one revolution every 90 minutes.

The stepper motor is a brushless permanent magnet DC stepper motor having a four phase winding and a 1.8° step angle. The stepper motor was selected because of its reliability and simplicity of construction. It contains no brushes or commutators or rubbing mechanical parts.

The harmonic drive produces a speed reduction of 100:1; it is simple, having only three major parts: the circular spline, the flexspline and the wave generator. The 100:1 ratio avoids excessively fine teeth and is the upper limit recommended by the manufacturer for this size. The materials used in the harmonic drive are 321 stainless and 17-4 PH CRES.

The assembly is dry lubricated with bonded moly disulfide films. The only exception is a small quantity of Krytox grease in the harmonic drive.

The drive characteristics are as follows:

Motor

1 revolution per day	0.1 watt
1 revolution per 90 minutes	0.6 watt
Weight	3.5 lbs.

Electronics

5 vdc and 28 vdc available	
Power	1 watt
Weight	1 lb.

Two configurations were considered for the solar array drive, external to the rotary transformer and concentric with the rotary transformer. The concentric drive results in a smaller overall length than the external drive and is also less complex than the external approach. It was decided that the concentric drive was the more advantageous and this approach was selected. These configurations are shown in Figure 3.9 and 3.10.

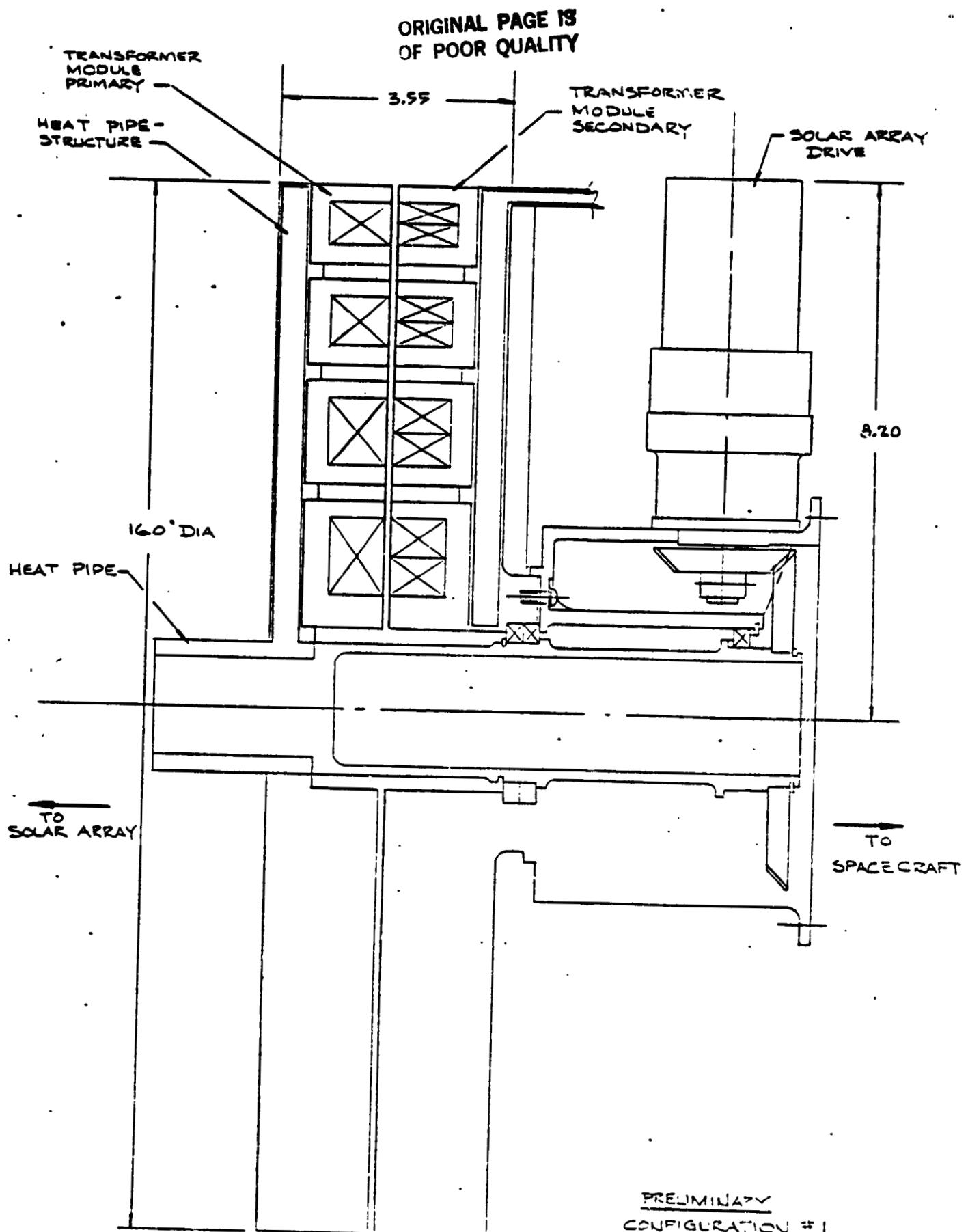


Figure 3-9.

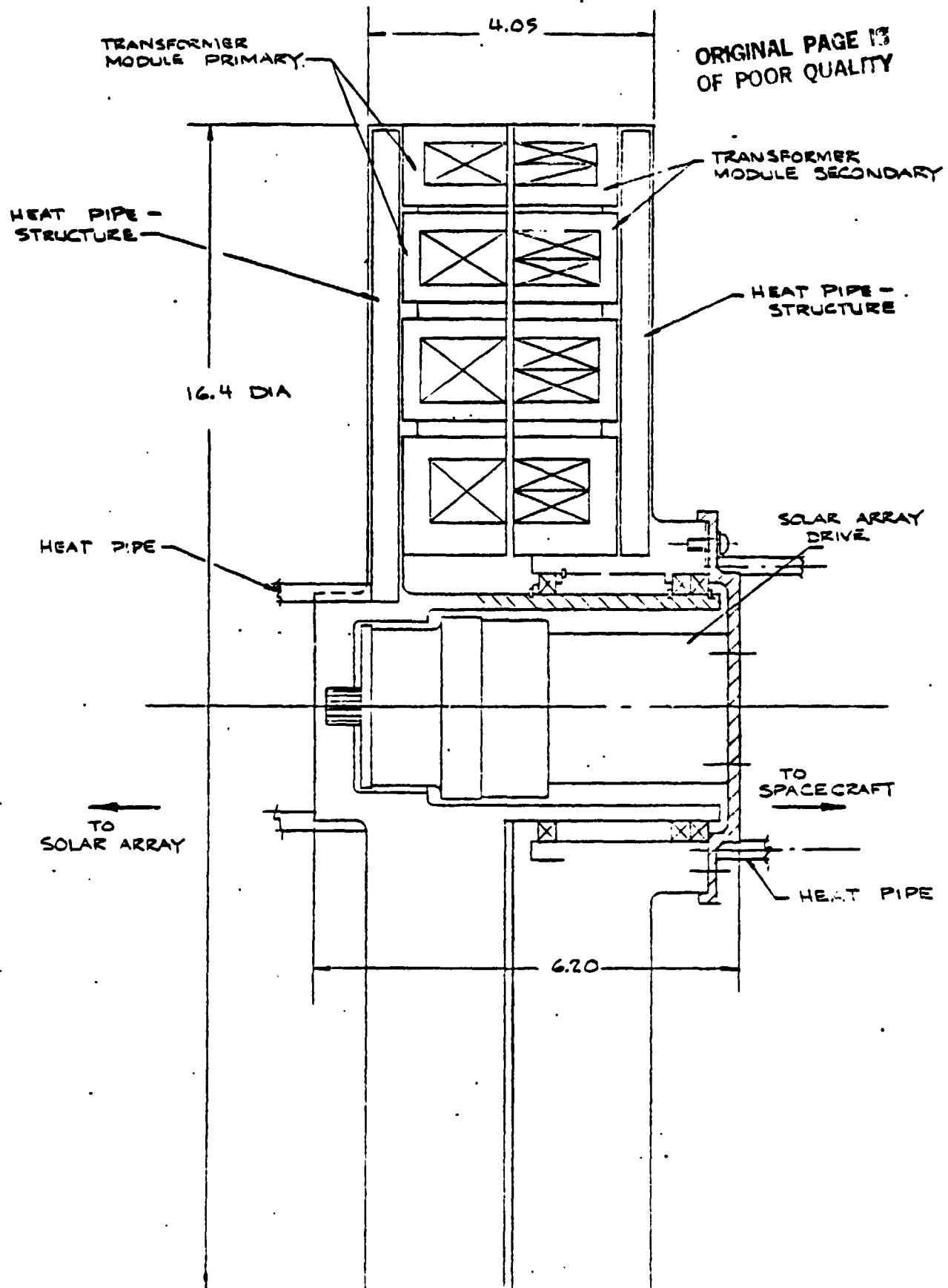


Figure 3-10.

PRELIMINARY

CONFIGURATION #2
100 KW ROTARY TRANSFORMER,
CONCENTRIC DRIVE,
FOUR 25 KW MODULES

3.8 POWER CONDITIONING ELECTRONICS

The power conditioning electronics for the radial gap rotary transformer will be the same as previously designed for the axial gap transformer. This consisted of a Schwarz resonant circuit having a switching frequency of 20 KHz. Each transformer module has its own independent set of electronics capable of providing 25 KW of electrical power. Figure 3.11, 25 KW Module - Resonant Converter shows the circuit technology. Complete design details for the power conditioning electronics were presented in NASA Report CR-165431, pp. I-5 to I-23.

The following are the power conditioning electronics parameters:

Input Power 25 KW/module

Input Voltage 440 volts, dc

Input Inductance 75 μ H

Weight

25 KW Module 19 lbs.

100 KW 76 lbs.

Radiator, 100 KW, 60° Bias 11.8 lbs.

Power Loss, 100 KW 2000 Watts

Efficiency 98.0%

These characteristics were used in this study to define the weight and efficiency of the rotary transfer device.

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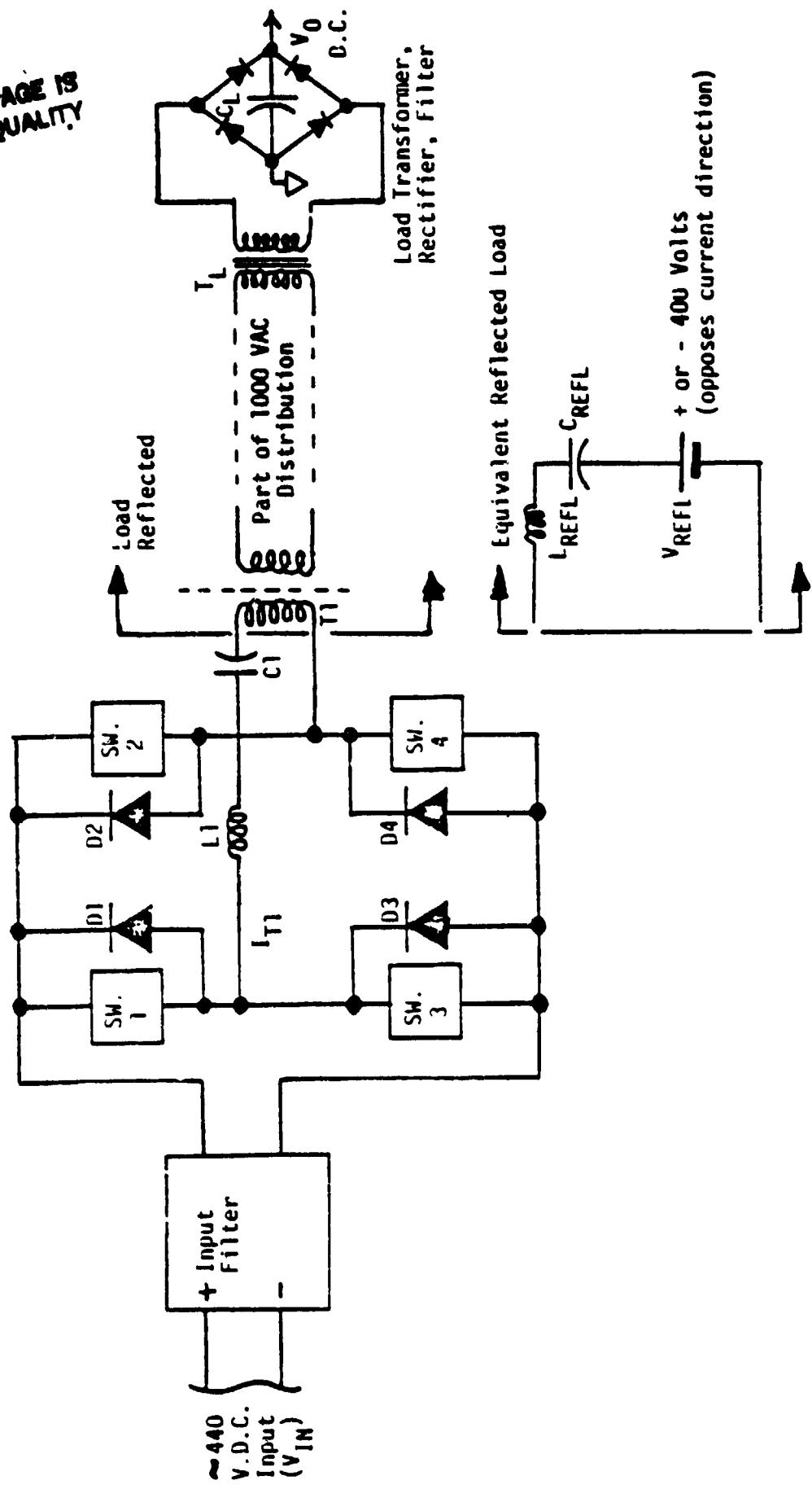


Figure 3-11. 25kW Module-Resonant Converter

4.0 RESULTS

This study demonstrates the feasibility of achieving a pancake rotary transformer geometry capable of transferring 100 KW of electrical power across a rotary interface. The rotary transformer consisted of 4-25KW having radial gaps. The rotary transformer is 17.3" in diameter, 2.625" long and weighs 75.7 lbs. The transformer losses are 1357 watts and its efficiency is 98.66 percent. The rotary power transfer device consisting of the transformer, structure, heat pipes, drive and power conditioning weights 225.4 lbs. and has an efficiency of 96.74 percent.

The rotary transformer does not require materials or technologies which are beyond the present state of the art. The area which might necessitate development is the heat pipes. The heat pipes are somewhat complex incorporating radial and axial heat transfer, and fabricated from Inconel. The ferrite cores for the outer modules are large in diameter and care would have to be exercised in their fabrication and assembly to prevent breakage because of their brittleness. Other parts for the rotary transformer, Litz wire, bobbins, adhesives and the drive mechanism are obtainable.

Based on this study, it appears that radial gap transformers in a pancake configuration can handle power levels of 25 KW to 100 KW using 25 KW modules. Power levels somewhat in excess of 100 KW can be achieved by using larger modules or additional modules. However, as the power levels approach 200 KW, the overall diameter of the transformer will become quite large resulting in very inefficient use of core materials and additional mechanical, structural and fabrication problems. Although no design studies were made, it appears that the requirements for the transfer of power levels of 200 KW would be best achieved by having two sets of 4-25 KW modules. The use of two sets of modules while introducing mechanical, structural and heat pipe problems, appears to be a more satisfactory alternate to further increases in diameter.

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4.1 WEIGHT

An analysis was made of the weight of the rotary transformer; and, for comparison purposes, the weight of the rotary power transfer device which consists of the rotary transformer, structural and mechanical parts, drive mechanism radiations and power conditioning. As will be seen, the rotary transformer assembly weighs approximately one-half of the weight of the complete power transfer device and the rotary transformer contributes about one-third of the total weight.

Rotary Transformer

The rotary transformer consists of 4-25 KW modules arranged concentrically. The weight of each 25 KW module is as follows:

Module Weights
(lbs.)

Module	Primary Copper	Core	Secondary Copper	Core	Total Primary	Total Secondary	Overall
1	1.2	4.4	1.5	4.2	5.6	5.7	11.3
2	1.2	6.4	1.7	5.7	7.6	7.4	15.0
3	1.7	7.6	2.6	7.5	9.3	10.1	19.4
4	2.1	10.5	3.1	9.3	12.6	12.4	25.0
	-	-	-	-	1.5*	1.5*	3.0
Total	6.2	28.9	8.9	26.7	36.6	37.1	73.7

* Epoxy, bobbins, miscellaneous.

100 KW Rotary Transformer Weight
4-25 KW Modules

Primary	36.6 lbs.
Secondary	37.1 lbs.
Hardware	2.0 lbs.
TOTAL	25.7 lbs.

Mechanical and Structural Parts

The weight of the mechanical and structural parts for the rotary transformer are as follows:

Structure	30.6 lbs.
Heat Pipes	14.5 lbs.
Bearings	.8 lbs.
Hardware	2.0 lbs.
Miscellaneous	3.0 lbs.
TOTAL	50.9 lbs.

Radiators

The weight of radiators required for the dissipation of the transformer losses assuming an 80°C base temperature is 6.5 lbs.

Drive Mechanism

The weight of the drive and its associated control is as follows:

Drive	3.5 lbs.
Control (5 & 28 volts provided)	1.0 lbs.
TOTAL	4.5 lbs.

Power Conditioning

The weight of the power conditioning electronics is estimated as

25 kw Module	9 lbs.
100 kw	76 lbs.
Radiator, 60°C base, 100 kw	11.8 lbs.

100 KW Rotary Power Transfer Device Weight

Rotary Transformer	75.7 lbs.
Structure, Heat Pipes, etc.	50.9 lbs.
Rotary Transformer Assembly (Sub-Total)	126.6 lbs.
Radiators (Rotary Transformer)	6.5 lbs.
Drive	4.5 lbs.
Power Conditioning Electronics & Radiator	87.8 lbs.
Rotary Power Transfer Device	225.4 lbs.

4.2 SIZE

The objective of achieving a pancake transformer geometry was attained. This was accomplished by using a radial gap transformer geometry and placing the transformer modules concentrically one-inside-another. The size of the 100 KW rotary transformer and the entire 100 KW rotary power transfer device is

	Diameter (in.)	Length (in.)
100 KW Rotary Transformer	17.3	2.625
100 KW Rotary Transfer Device	17.3	6.60

4.3 LOSSES

The magnitude of losses in the rotary transformer are limited by the allowable temperature rise of the core and winding, and the effectiveness of the heat rejection system. A summary of radial transformer losses is as follows:

Rotary Transformer

Losses (Watts)

Module	Primary		Secondary	
	Copper	Core	Copper	Core
1	95	45	91	43
2	99	67	89	60
3	134	58	101	57
4	143	80	125	70
Sub-Total	471	250	406	230
Sub-Total	721		636	
Total	1352			

Module	Primary	Secondary	Total
1	140	134	274
2	166	149	315
3	192	158	350
4	223	195	418
Total	721	636	1357

100 KW Rotary Transformer Losses

Primary	721 Watts
Secondary	636 Watts
Total	1357 Watts
Efficiency	98.66%

Mechanism

5 Watts

Power Conditioning

25 KW Module	500 Watts
100 KW	2000 Watts
Efficiency	98.0%

Overall System

Rotary Transformer, Power Conditioning and Drive Loss	3362 Watts
Efficiency	96.74%

4.4 TEMPERATURE

The temperatures of the transformer modules based upon an 80°C sink are as follows:

Module	Primary Winding	Core	Secondary Winding	Core
1	124°C	105°C	123°C	104°C
2	124°C	103°C	119°C	99°C
3	115°C	99°C	111°C	97°C
4	119°C	105°C	111°C	101°C

5.0 COMPARISON OF RADIAL AND AXIAL GAP ROTARY TRANSFORMERS

A comparison was made of the characteristics of the radial gap rotary transformer designed as part of this study with the axial gap rotary transformer designed as part of the Preliminary Design Development of 100 KW Rotary Power Transfer Device, Report NASA CR-165431. The radial and axial gap transformers have the same requirements of power, frequency, voltage input and output, temperature, and inductance. The transformers were designed on a similar basis: 4-25 KW modules, parallel secondary windings, ferrite cores, Litz wire, and a heat pipe thermal system. The major differences were radial vs. axial gaps, and the overall pancake configuration. The many similarities permit a comparison between the two rotary transformer geometries for weight, size, losses, efficiency and temperature. In order to be comprehensive, comparisons will be made not only of the rotary transformers but of the complete power transfer device including structure, drive and heat pipes.

It should be noted that some of the weight or other parameters stated in this section might differ slightly from those elsewhere in other sections of this report. Any differences are due to "bookkeeping" procedures and not alter the significance of the results.

5.1 Weight Comparison

Although both the radial and axial gap rotary transformers consist of 4-25 KW modules, the radial gap transformer modules are all different from each other while the axial gap modules are all the same. The weights of these types of transformers must be compared both on the module level and for the entire transformer assembly. These weights are as follows:

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Rotary Transformer Modules (25 KW)
Weight (lbs.)

Module	Radial Gap				Axial Gap			
	Primary		Secondary		Primary		Secondary	
	Copper	Core	Copper	Core	Copper	Core	Copper	Core
1	1.2	4.4	1.5	4.2	1.1	2.1	1.8	3.3
2	1.2	6.4	1.7	5.7	1.1	2.1	1.8	3.3
3	1.7	7.6	2.6	7.5	1.1	2.1	1.8	3.3
4	2.1	10.5	3.1	9.3	1.1	2.1	1.8	3.3
Shunts	-	-	-	-	1.1	2.1	-	.7
Subtotal	6.2	28.9	8.9	26.7	4.4	8.4	7.2	16.0
Subtotal	35.1		35.6		12.8		23.2	
TOTAL	70.7				36.0			

100 KW Rotary Transformer
Weight (lbs.)

	Radial Gap*	Axial Gap*
Copper Weight	15.1 lbs.	11.6 lbs.
Core Weight	55.6 lbs.	24.4 lbs.
Total Weight	70.7 lbs.	36.0 lbs.

* Not including epoxy, leads, miscellaneous, hardware, etc.

The weight of the radial gap transformer is 70.7 lbs. as compared with 36.0 lbs. for the axial gap. The difference in weight is primarily due to less efficient use of materials and a somewhat more conservative radial gap transformer design. The usage of material, primarily ferrite cores, is the results of mechanical and fabrication considerations. From a mechanical design consideration, the yokes were wider than necessary on the outermost modules so that all modules would have the same width.

The poles were kept to a minimum thickness of .2 inches to prevent breakage during fabrication.

Thermally, the design of the radial gap transformer was more conservative than the axial gap to allow more margin should the heat pipe be less effective than anticipated. A comparison of the temperatures of the transformers is as follows:

	Axial Gap	Radial Gap			
		Module 1	2	3	4
Core	115°C	105°C	103°C	99°C	105°C
Winding	138°C	124°C	124°C	115°C	115°C

It is reasonable to assume that the weight of the radial gap rotary transformer can be reduced by design optimization, and by increasing the temperature of the cores and windings to values closer to their allowable limits. The table below shows a comparison of rotary transformer with 10 percent, 20 percent, and 30 percent reductions in weight. A 10 percent weight reduction would be easy to achieve, while a 30 percent could be difficult to achieve.

Weight Reduction

Transformer Weight Reduction Base	Radial Gap (lbs)				Axial Gap (lbs)
	10%	20%	30%		
70.7	63.6	56.6	49.5		
34.7*	27.6*	20.6*	13.5*		36.0

* Weight differential Radial Gap and Axial Gap

Considering the complete radial gap rotary power transfer device having a 20 percent weight reduction in the transformer; a 10 percent reduction in the structure, heat pipes, etc., and no reduction in the weight of drive, radiators and power conditioning, a weight comparison with the axial configuration would be as follows:

Power Transfer Device Weight (lbs)

	Radial Gap		Axial Gap
	Baseline Design	Weight Reduction	
Rotary Transformer	75.7	60.6 (-20%)	46.4
Structure, Heat Pipes	48.5	43.7 (-10%)	43.5
Drive	4.0	4.0	7.6
Radiators	6.5	6.5	6.5
Power Conditioning	87.8	87.8	87.8
Total	222.5	202.6	191.8
Weight Differential (Radial vs. Axial)	30.7	10.8	-

Thus, the overall weight of the radial gap transformer is between 10.8 lbs. and 30.7 lbs. heavier than an axial gap transformer which may not be significant from the aspect of total system weight.

5.2 COMPARISON OF LOSSES AND EFFICIENCY

The losses in the radial and axial gap transformers are as follows:

Module	Losses (Watts)					
	Primary	Radial Gap Secondary	Total	Primary	Axial Gap Secondary	Total
1	140	134	274	170	167	337
2	166	149	315	170	167	337
3	192	158	350	170	167	337
4	223	195	418	170	167	337
Subtotal	721 Watts	636 Watts		680 Watts	668 Watts	
Total	1357 Watts			1348 Watts		
Efficiency	98.66%			98.67%		

The total losses in the radial and axial gap transformers are almost identical, 1357 watts vs. 1348 watts. This was not done deliberately as part of the design effort, but coincidental. The losses of the individual modules, however, vary considerably: between 274 watts and 418 watts for the radial gap; and 337 watts for the axial gap. Since the losses in the transformers are nearly identical, their efficiencies will be practically identical 98.66% and 98.67%.

5.3 SIZE COMPARISON

The radial gap rotary transformer had the desired pancake geometry; large diameter, short length. In comparison, the axial gap transformer was tubular having a small diameter and long length. Comparable dimensions for the radial and axial gap rotary transformers and rotary transfer devices are as follows:

	Radial Gap Diameter (in.)	Length (in.)	Axial Gap Diameter (in.)	Length (in.)
100 KW Rotary Transformer	17.3	2.625	7.43	14.3
100 KW Rotary Power Transfer Device	17.3	6.60	7.43	16.25

It is interesting to note that the diameter of the radial gap power transfer device is approximately the same as the length of the axial gap power transfer device; while the length of the radial gap is approximately the same as the diameter of the axial gap device. This was not done deliberately as part of the design, but coincidental.

5.4 DRIVE MECHANISM COMPARISON

The drive mechanism used for the axial gap rotary transformer consisted of a stepper motor, harmonic drive speed reducer, spur gear set and wrap spring clutches. The drive contained two redundant unidirectional drives interconnected by two wrap spring clutches which permitted either or both drives to be energized. The resultant output torque is 20 ft.lbs. and 40 ft.lbs., respectively.

The drive mechanism used for the radial gap rotary transformer was somewhat different. In order to save room and to preserve the pancake geometry, the drive was placed internal to and concentric with the transformer modules. Gearing and redundancy are not provided. The output torque is 3 ft.lbs.

A weight and power comparison of the two drive systems is as follows:

	Radial Gap Drive	Axial Gap Drive
Motor		
1 Revolution per dg	.1 Watt	1 Watt
1 Revolution per 90 min.	.6 Watts	4 Watt
Weight	3.0 Lbs.	6.6 Lbs.
Electronics		
5 vdc & 28 vdc available		
Power	1 Watt	1 Watt
Weight	1 Lb.	1 Lb.

Although the output torque of the drive mechanism for the radial gap transformer is less than that for the axial gap, it is adequate for the application. If more torque or redundancy is desired, it can be incorporated into the design, but will entail more complexity and room.

5.5 RELIABILITY COMPARISON

Although the radial gap rotary transformer is very similar to the axial gap transformer in many respects; ferrite cores, Litz wire windings, and heat pipes, a preliminary assessment of the two concepts indicates that the radial gap configuration could be potentially somewhat less reliable. The following tabulation shows aspects of the two approaches which are potential sources of reduced reliability.

Radial Gap Rotary Transformer

- Large diameter ferrite cores
- Combined radial and axial heat pipes
- Magnetic attractive forces between primary and secondary
- Non-redundant drive
- Structural rigidity

Axial Gap Rotary Transformer

- Thermal path length between secondary winding and core
- Connection of leads to winding
- Accessibility of winding leads, heat pipes
- Replacement of defective module

Care would be exercised in the design and fabrication to prevent obvious causes of failure. There are no reasons why either approach is inherently unreliable or should be avoided.

6.0 RECOMMENDATIONS

This study has shown that a radial gap rotary transformer is a feasible method for transferring 100 KW electrical power across a rotary interface. The following recommendations are made for future work:

1. Investigate heat pipe configurations for combined radial and axial transfer capability.
2. Fabricate a 25 KW, 20 KHz rotary transformer and power conditioning electronics.
3. Perform functional tests on rotary transformer and power conditioning electronics.

7.0 CONCLUSIONS

1. The radial gap rotary transformer is a feasible method for transferring electrical power of the magnitude of 100 KW across a rotary joint. No basic problems are anticipated for transferring up to 200 KW.
2. The efficiency of the 100 KW radial gap transformer is the same as the axial gap rotary transformer, 98.66%.
3. The radial gap transformer is heavier than the axial gap, but the heat pipe and structural weights are comparable.
4. The 100 KW radial gap transformer is 17.3" diameter, 2.625" long, and weighs 75.7 lbs.
5. The 100 KW rotary power transfer device is 17.3" diameter, 6.6" long and weighs 225.4 lbs.
6. Trade-off studies in the magnetic electrical, structural and thermal design areas could result in significant reductions in size and weight.
7. Thermal considerations impose size and weight limitations on the rotary transformer.

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